# Life Performance Prediction Approach for the Potential eMMRTG

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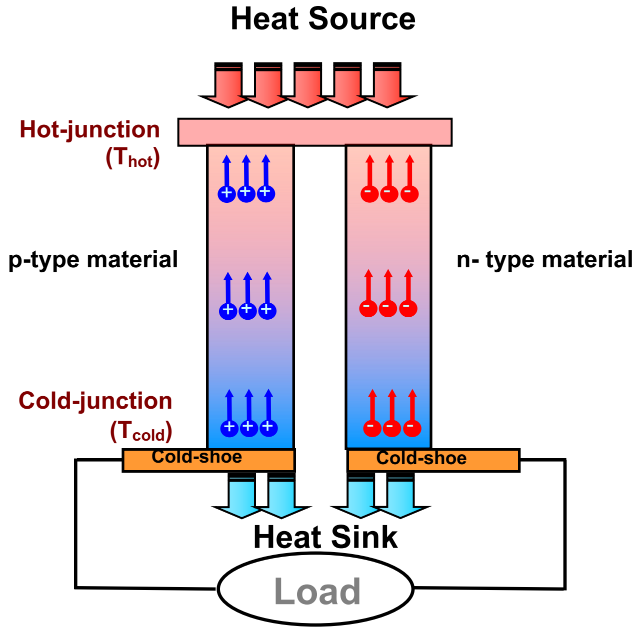
# Thermoelectric Power Generation

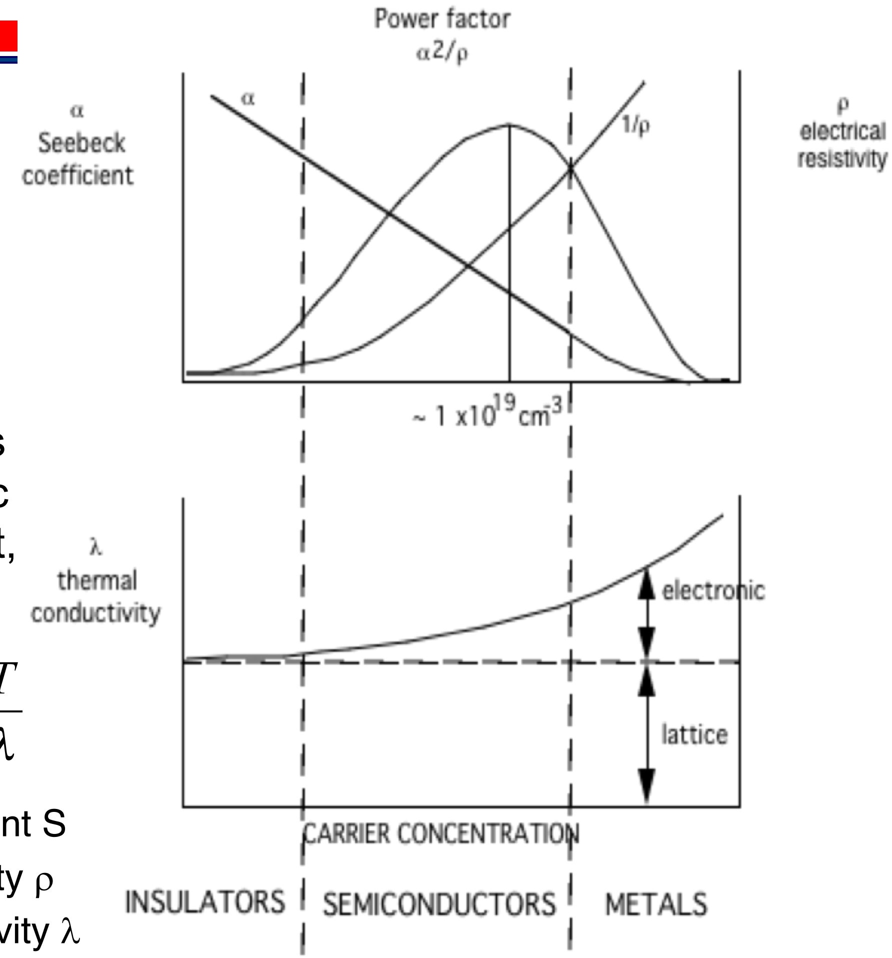
**Thermoelectric effects are defined by a coupling between the electrical and thermal currents induced by an electric field and a temperature gradient**




Dimensionless Thermoelectric Figure of Merit, ZT

$$ZT = \frac{\sigma S^2 T}{\lambda} = \frac{S^2 T}{\rho \lambda}$$

- Seebeck coefficient S
- Electrical resistivity ρ
- Thermal conductivity λ




## Conversion Efficiency

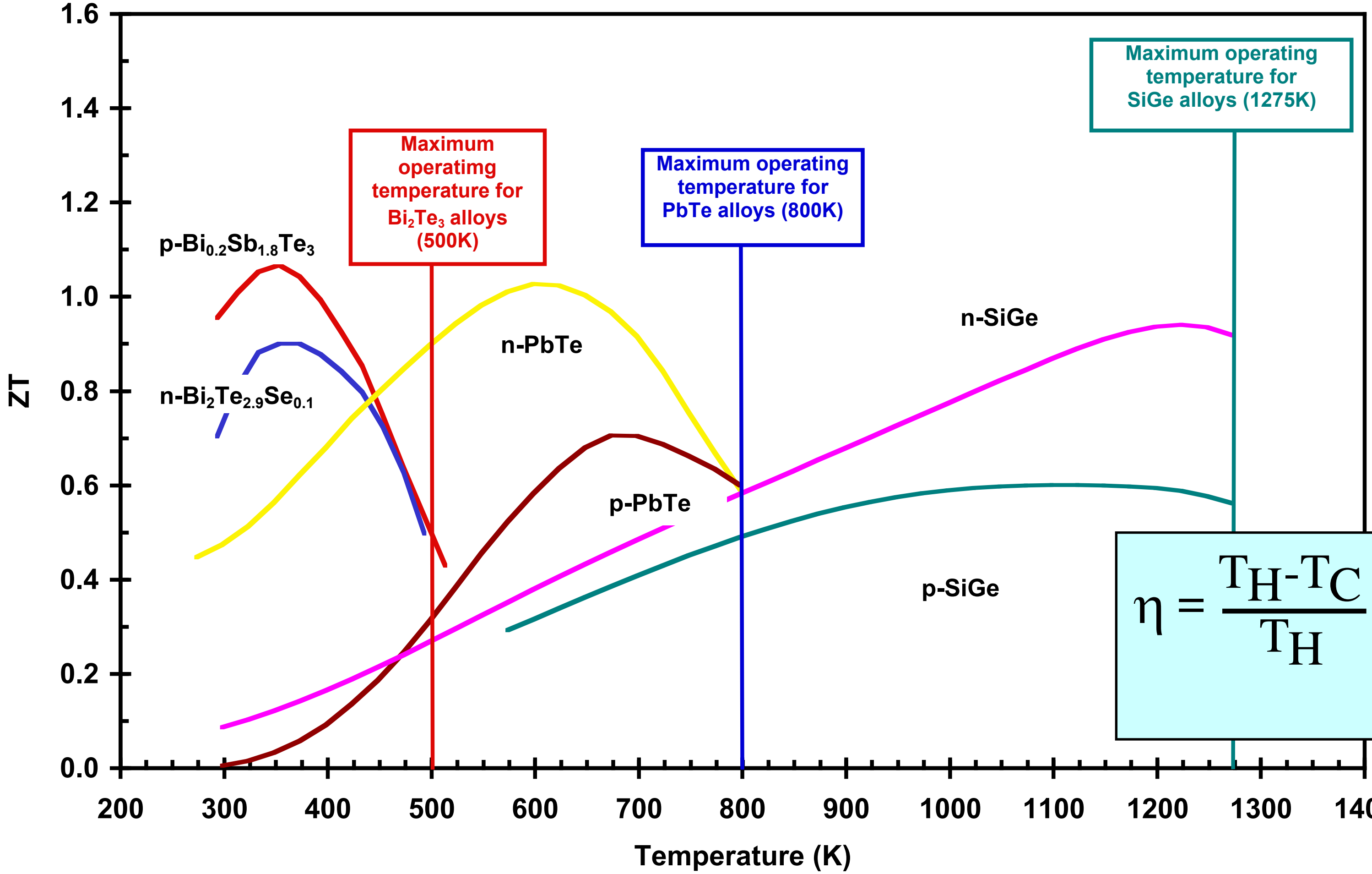
Carnot | TE Materials

$$\eta_{\max} = \frac{T_{hot} - T_{cold}}{T_{hot}} \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_{cold}}{T_{hot}}}$$

## Thermoelectric Couple

Conversion efficiency is function of ZT and ΔT

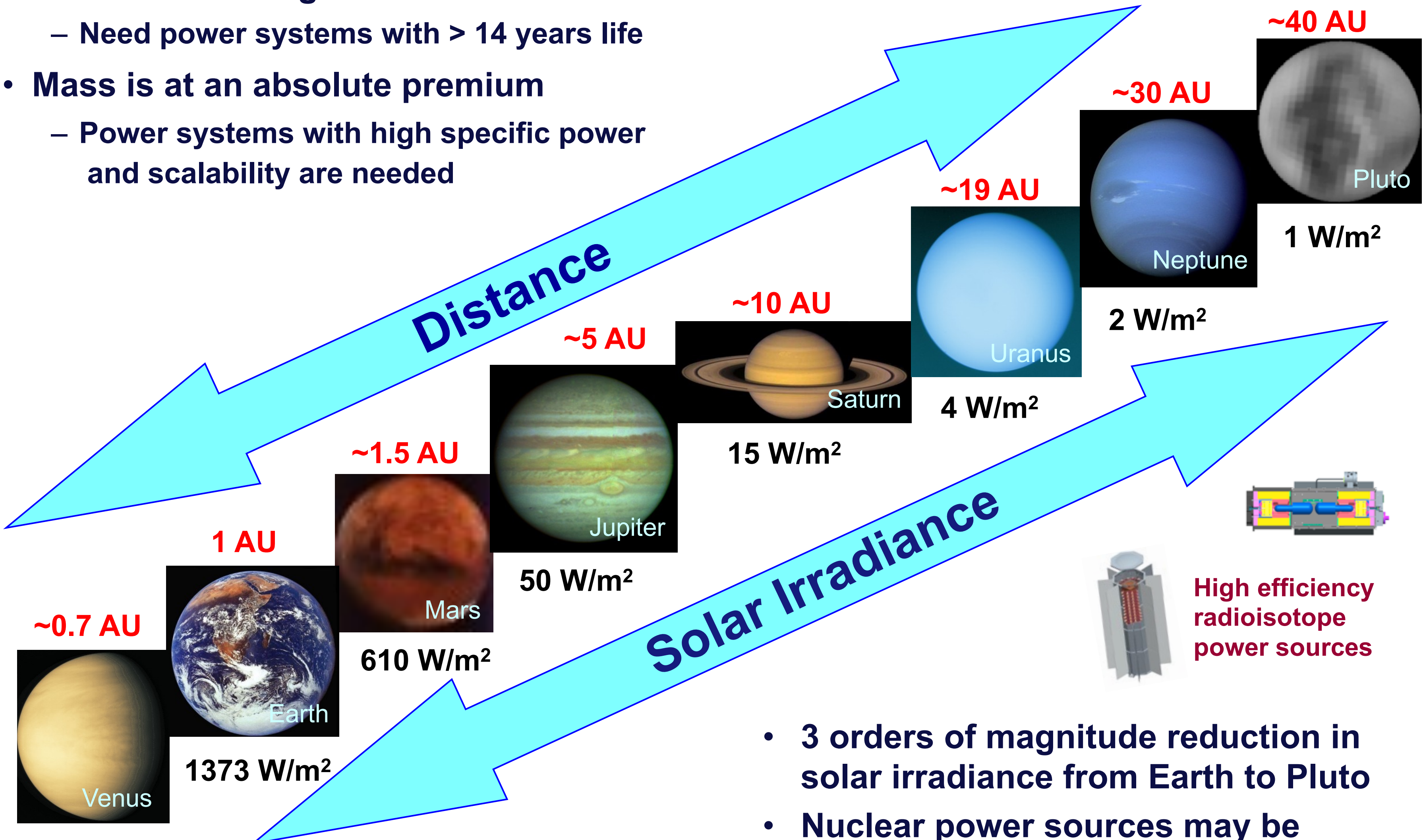
# State-of-Practice High-Temperature Thermoelectric Materials




$$\eta = \frac{T_H - T_C}{T_H} \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_C}{T_H}}$$

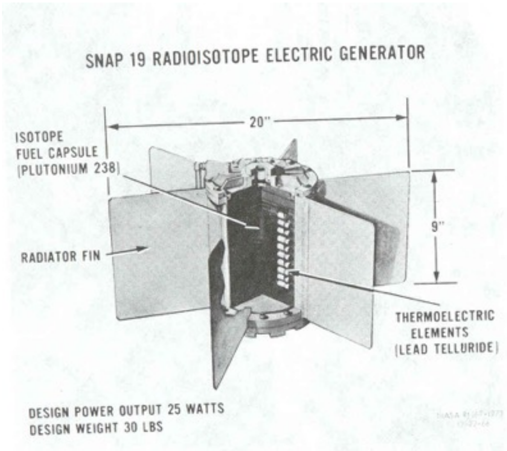
# Space Power Technology

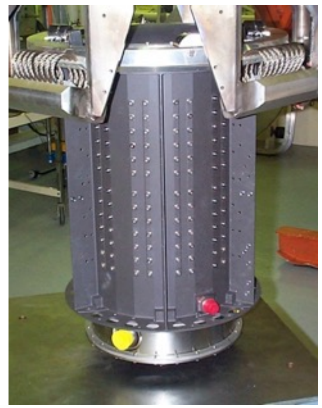
- Missions are long
  - Need power systems with > 14 years life
- Mass is at an absolute premium
  - Power systems with high specific power and scalability are needed

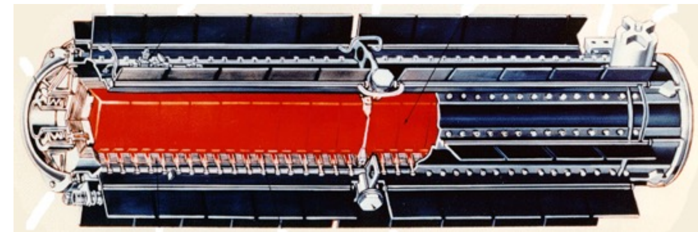



- 3 orders of magnitude reduction in solar irradiance from Earth to Pluto
- Nuclear power sources may be needed for some missions

# Flight Demonstrated Radioisotope Thermoelectric Generators
## (3 Most Recently Flown Designs)



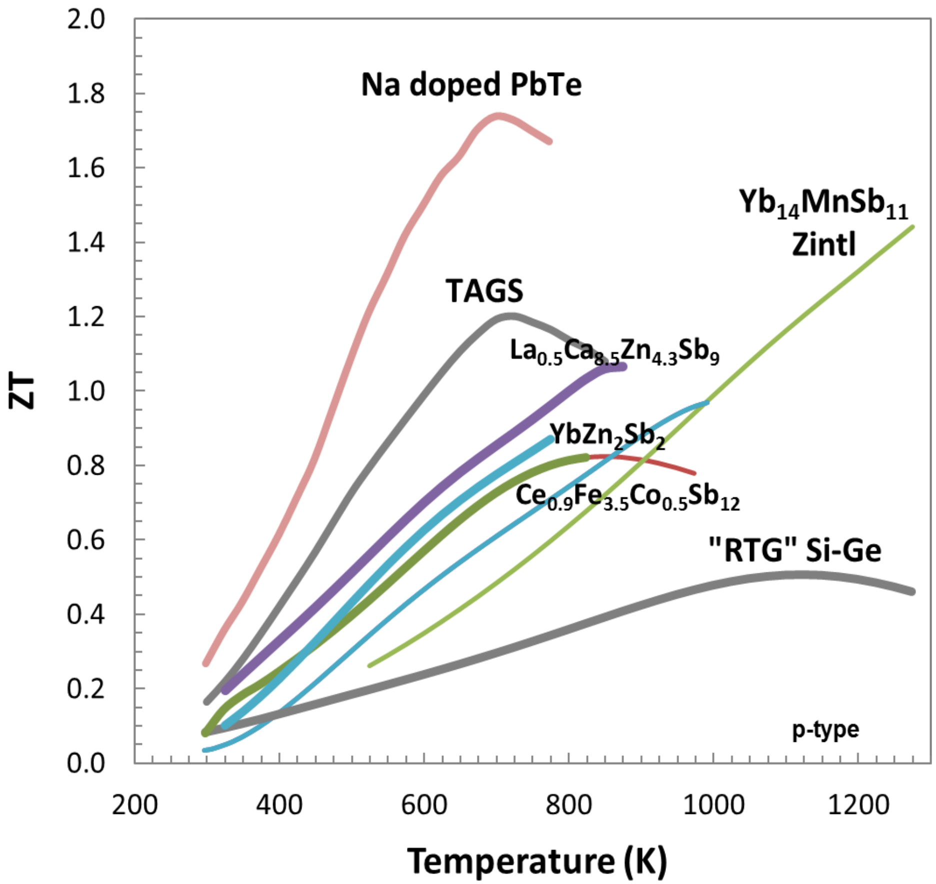



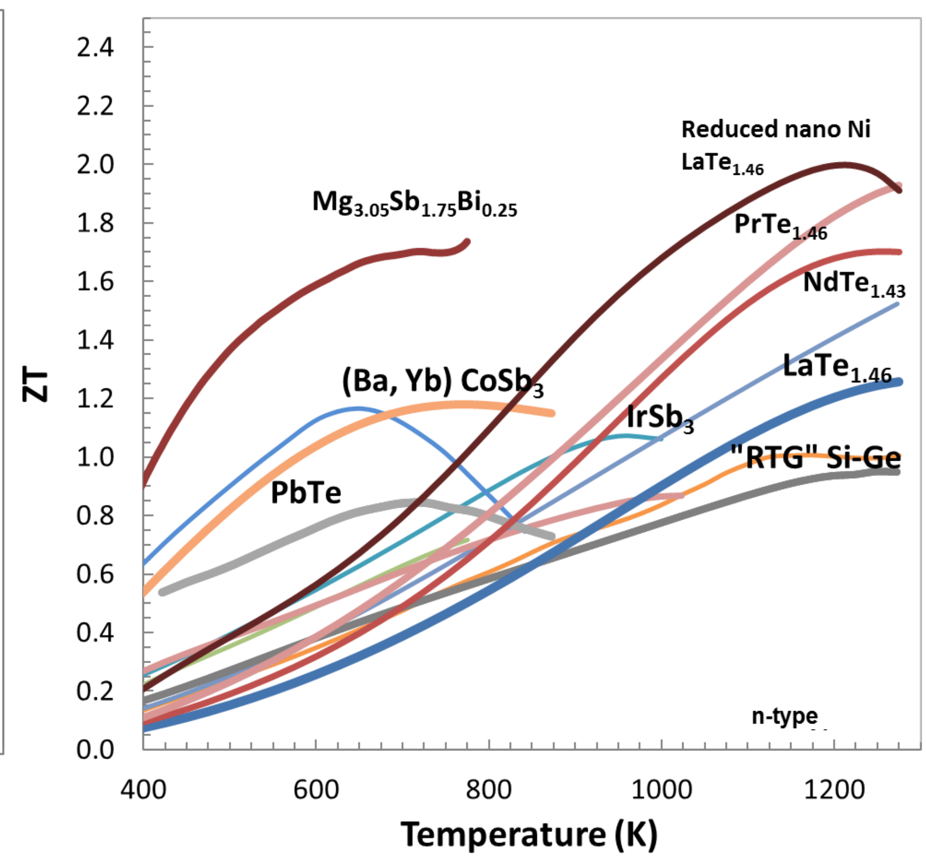


| SNAP-19 (PbTe/TAGS RTG) (1960-70's) | SiGe MHW RTG (1970's) | SiGe GPHS RTG (1980-2006) |
|---|---|---|
| 40.3 Watts (BOM) | 158 We (BOM) | 285 We (BOM) |
| 6.2 % system efficiency | 6.6 % system efficiency | 6.8% system efficiency |
| 3 We/kg | 4.2 We/kg | 5.1 We/kg |
| PbTe Thermoelectrics | SiGe Thermoelectrics | SiGe Thermoelectrics |
| $T_H$= 525C, $T_C$=210C | $T_H$= 1000C, $T_C$=300C | $T_H$= 1000C, $T_C$=300C |
| Nimbus B-1/III, Pioneer 10/11, Viking 1/2 | LES 8/9, Voyager 1/2 | Galileo, Ulysses, Cassini & New Horizons |

Past US Radioisotope Power Systems have used either PbTe or SiGe alloys thermoelectric materials

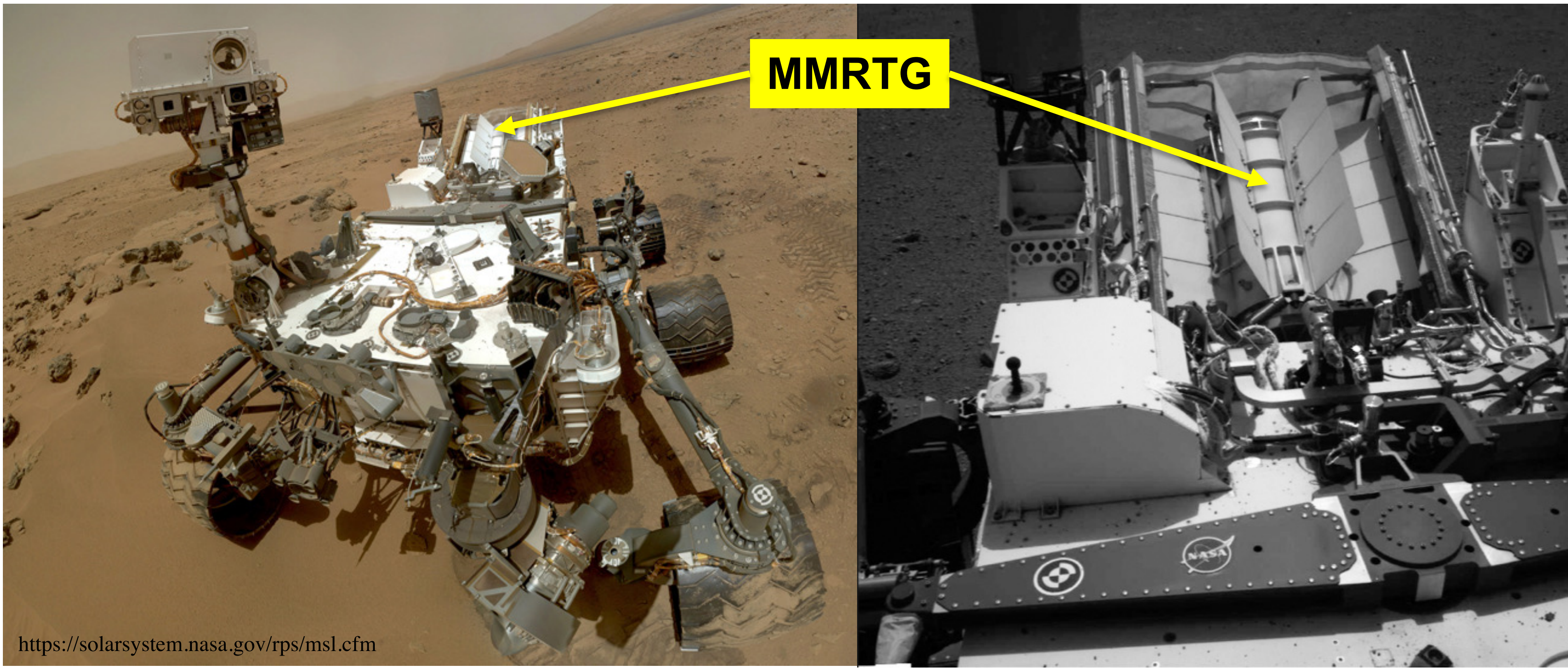
# JPL Advanced TE Materials



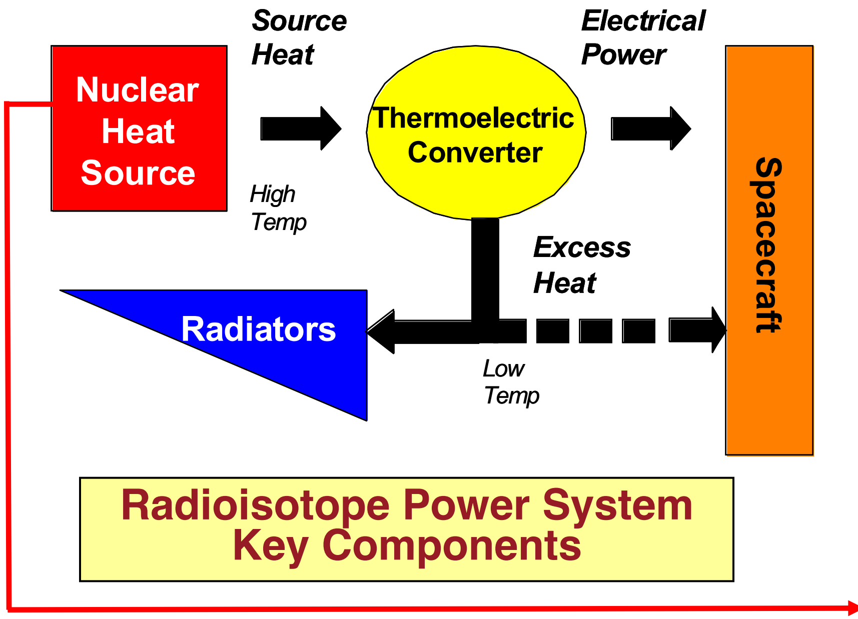

- **Best combination of TE materials predicted to result in ~ 18% couple-level efficiency**
- **Some advanced TE materials under development for device integration**

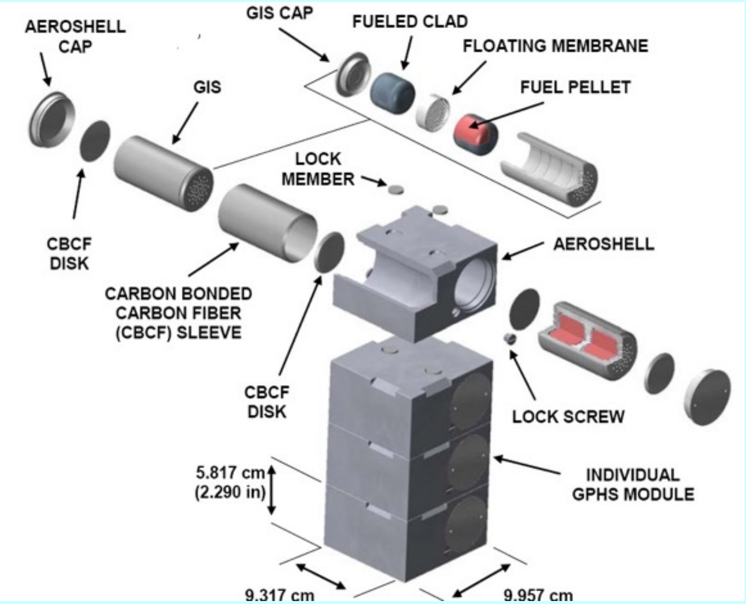
# MSL Curiosity Rover Powered by the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)



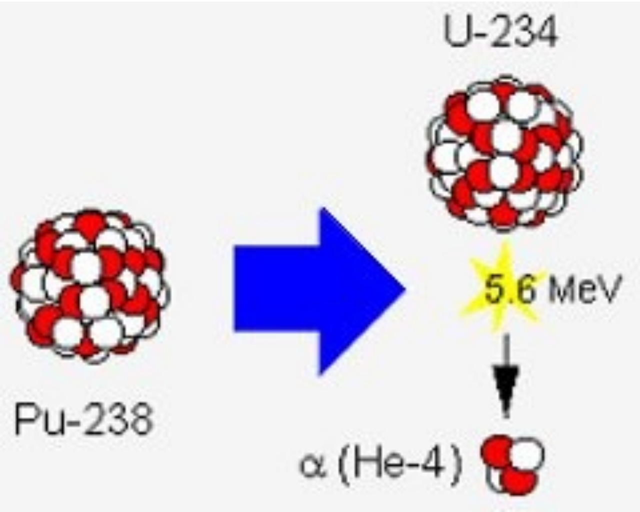

**MMRTG has successfully and reliably provided power and thermal energy to the Curiosity rover since August 2012. It will fly again on Mars 2020.**

# Radioisotope Thermoelectric Generator Key Components

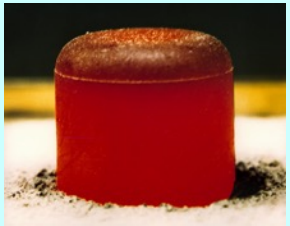



https://en.wikipedia.org/wiki/General-purpose_heat_source




- **General Purpose Heat Source (GPHS)**
  - Uses $^{238}Pu$
    - Decay
    - α emitter
    - 87.7 years half-life
  - 440 g $^{238}Pu$ per GPHS
  - 250 thermal Watts/GPHS
  - Heat flux ~ a few W/cm$^2$
  - $T_H$ > 1000C



# Filled skutterudites

**Many $RT_4Pn_{12}$ compounds exist such as $LaFe_4As_{12}$**

**Derived from $CoAs_3$ skutterudite prototype:**

- By filling the empty octants present in the unit cell

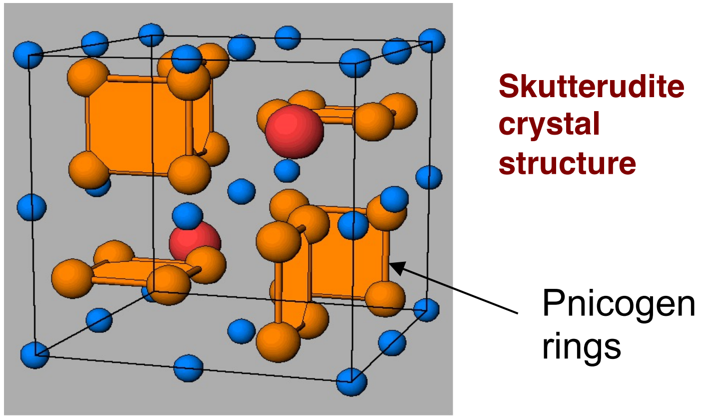
**Most have a metallic behavior**

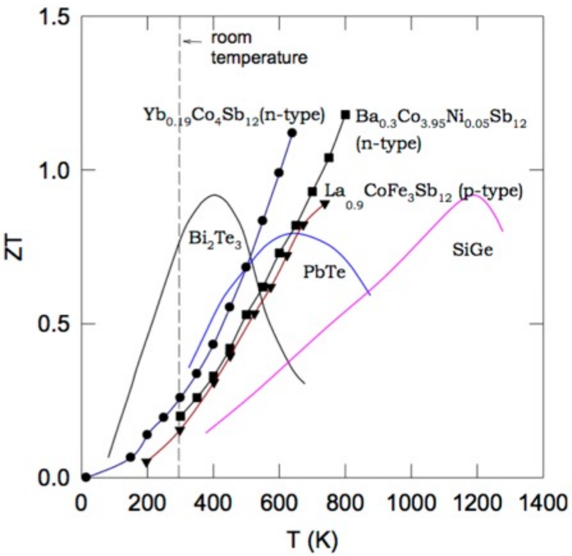
- Trivalent rare earth ($La^{3+}$) and divalent transition metal ($Fe^{2+}$)
- Valence electron count (1x3) + (4x8) + (12x3) = 71
- Count of 72 needed to conserve a semiconducting behavior

**Expected reduction in lattice thermal conductivity**

- "Rattlers"
- Conduction in valence band dominated by pnicogen rings ; potentially, no significant impact on carrier mobility

⇨ Phonon Glass Electron Crystal (PGEC) concept (G. Slack): decoupling of electrical and thermal transport i.e. conduct electricity like a perfect crystal with a glass-like thermal conductivity




Skutterudites have excellent thermoelectric properties with ZT > 1

# What is being enhanced in the Proposed eMMRTG?

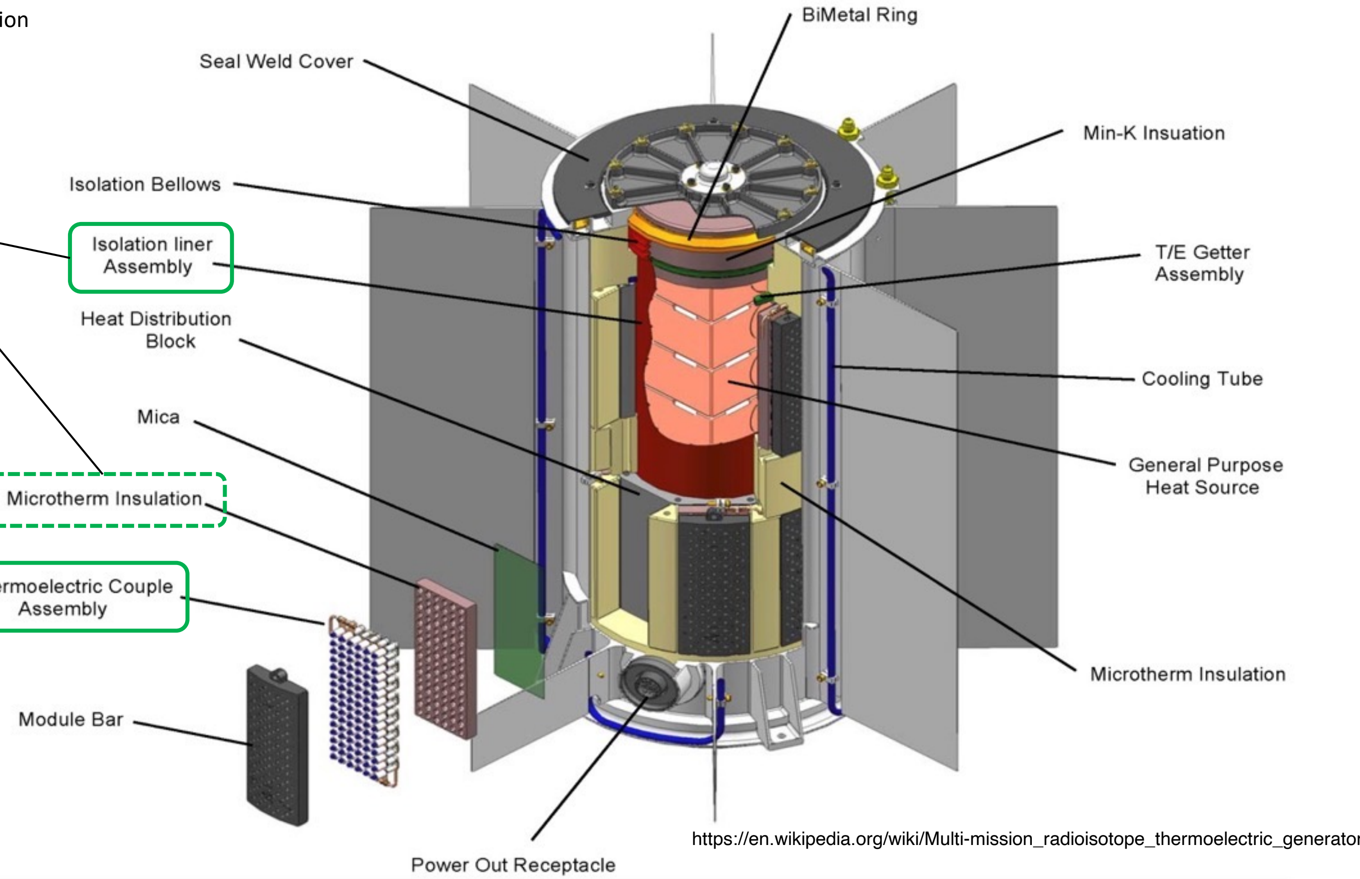
Enhancements under consideration

Known enhancements

Engineering: emissivity change to liner, substitute part of insulation

Changes needed to MMRTG

New Technology: Substitute skutterudite couples




https://en.wikipedia.org/wiki/Multi-mission_radioisotope_thermoelectric_generator

**Retrofitting the MMRTG with new skutterudite thermoelectric couples**

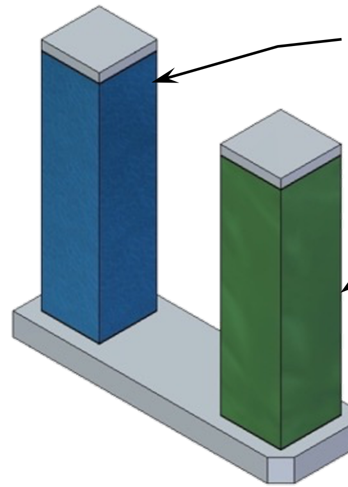
- Skutterudite couples fit within the space available (no change in number of couples, 768)
- Simple emissivity change to heat source liner will enable use of MMRTG end insulation system
- Volume, mass, and external interfaces remain unchanged
- Multi-mission capability preserved

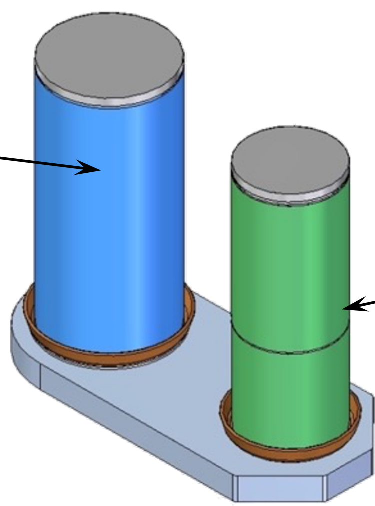
# T/E Couple Assembly Comparison

<u>“Drop-in Replacement” Couple</u>

- **Better high temperature capability**
- **Non-segmented**
- **Equivalent or better mechanical properties**
- **Smaller element cross section**
  - *Required to increase hot side temperature*

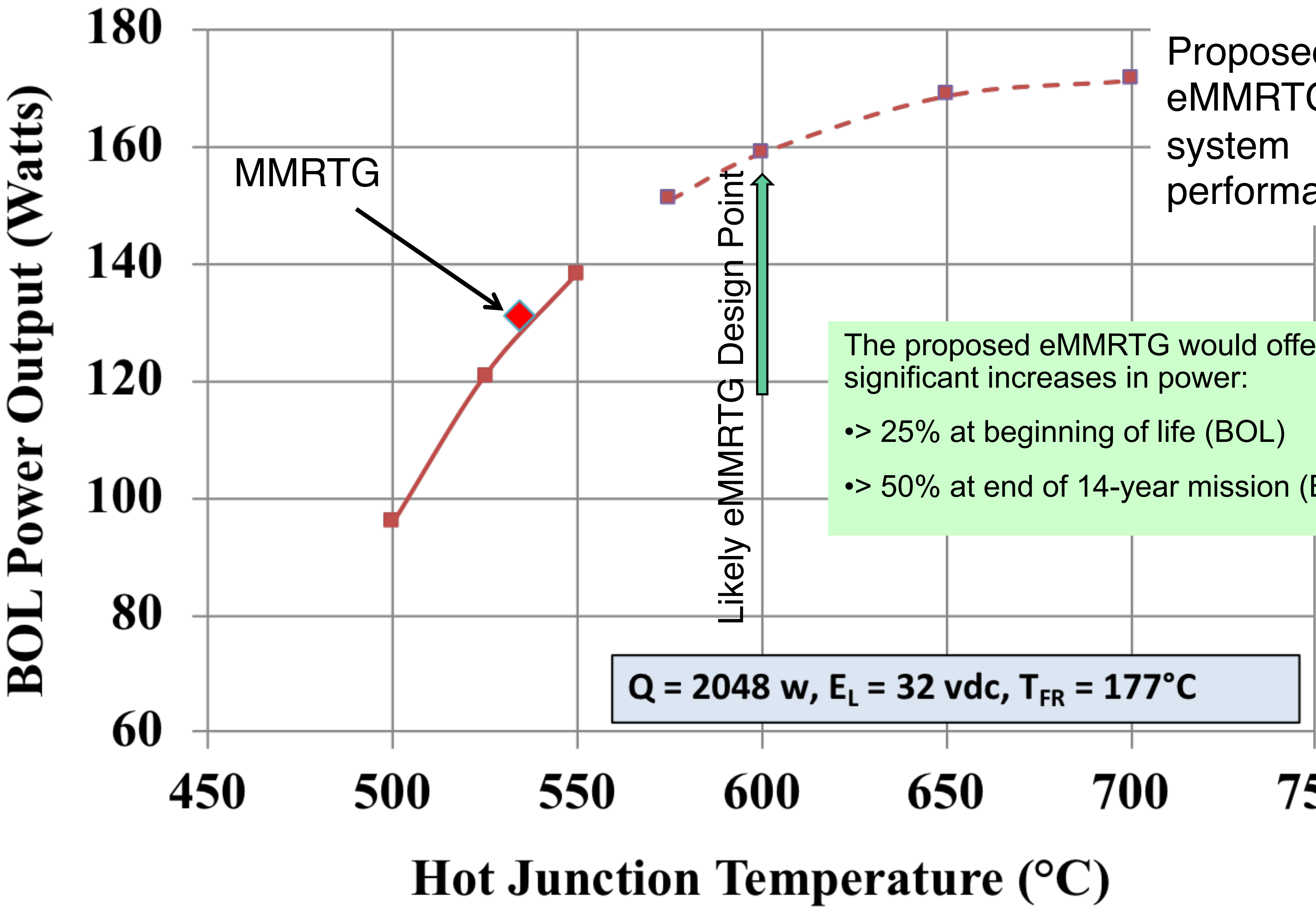
**Proposed eMMRTG Couple**




**MMRTG Couple**

# eMMRTG– Power vs. $T_{hot\text{-}junction}$

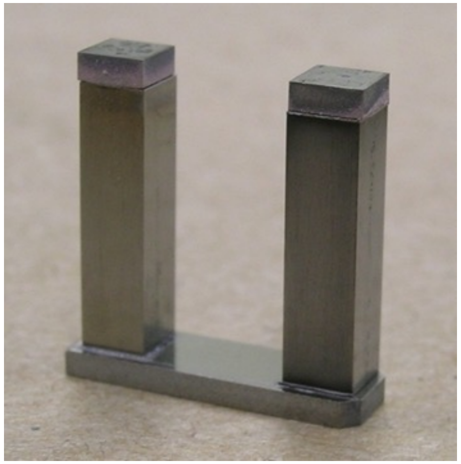



The proposed eMMRTG would offer significant increases in power:

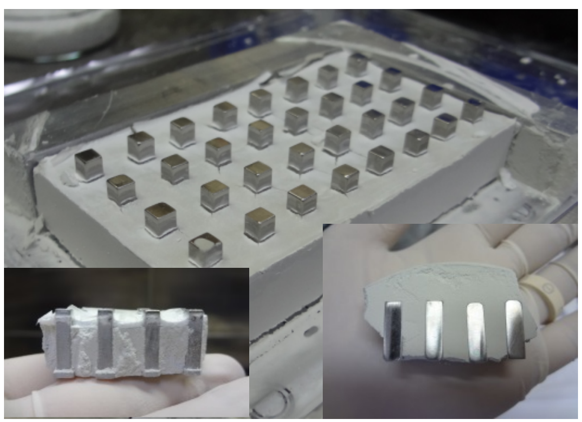
•> 25% at beginning of life (BOL)

•> 50% at end of 14-year mission (EOM)

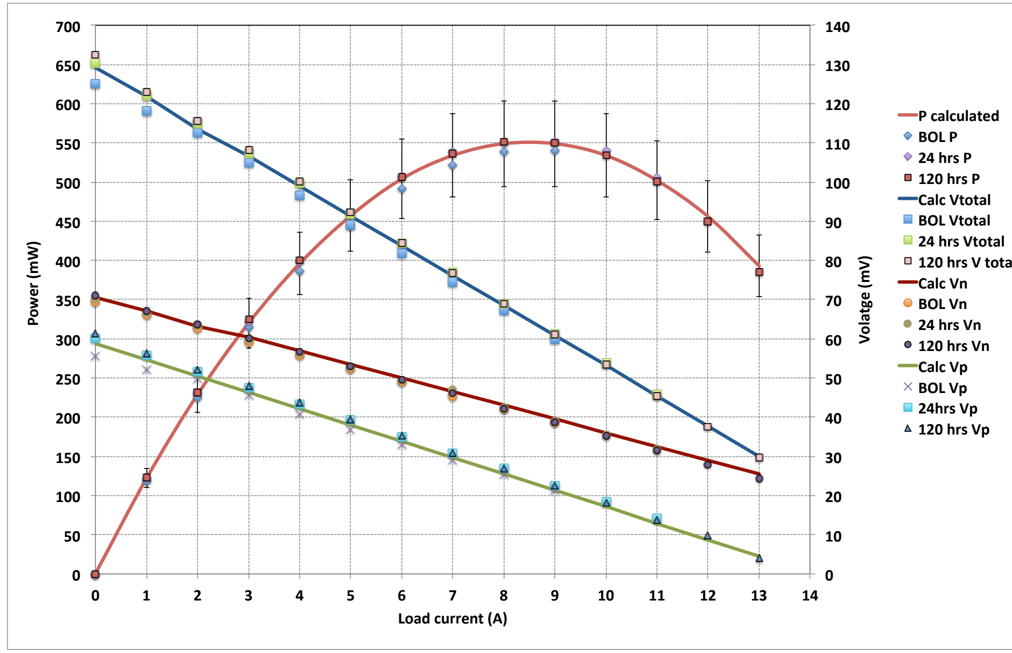
# Couple Fabrication, Encapsulation, and Performance



1st iteration SKD couple

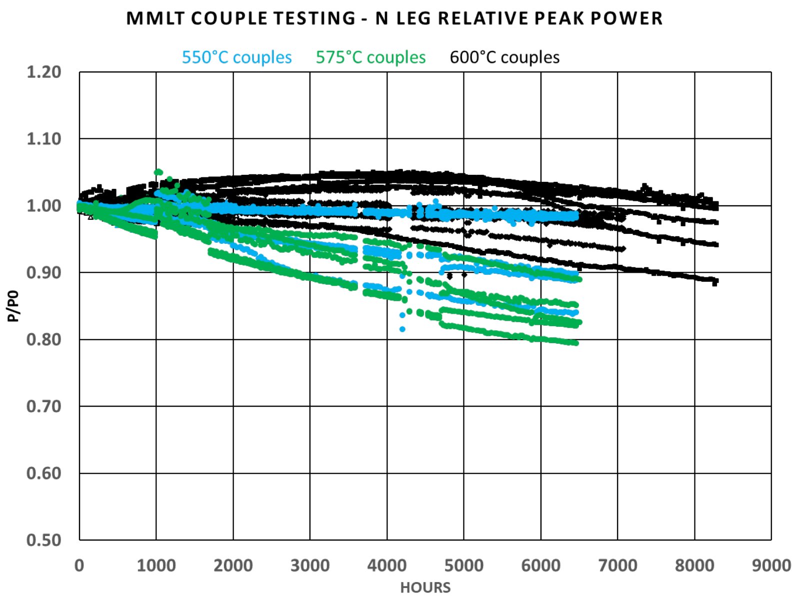


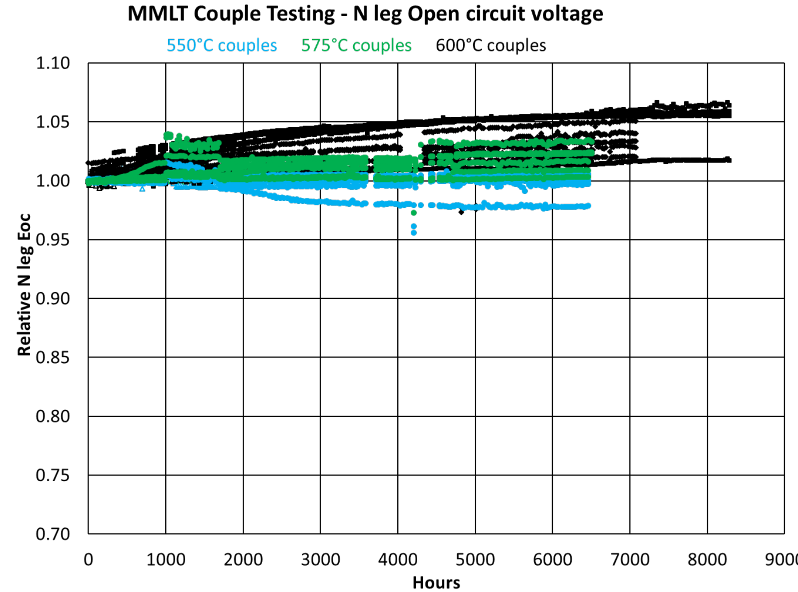
Critical Point Dried Aerogel Processed into a 4 x 8 Array of Couples

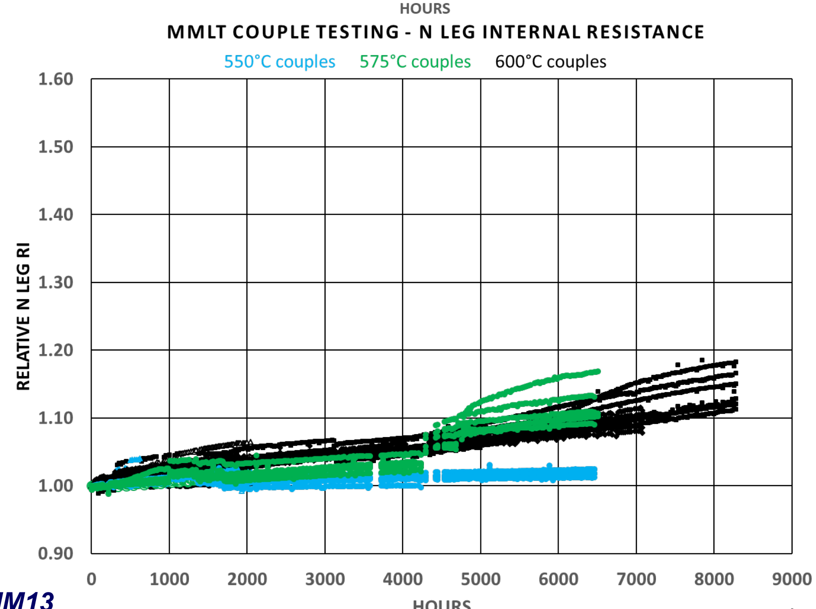



| | | | | Power at match-load | | | |
|---|---|---|---|---|---|---|---|
| Couple ID | $T_{Hot}$ | $T_{Cold\text{-}AVG}$ | $V_{OC}$ | $V_{load}$ (mV) | I (A) | P (mW) | Adj. P (mW) |
| SKD-64-1 | 601.6 | 199.9 | 133.6 | 66.55 | 3.57 | 237.7 | 234.0 |
| SKD-64-2 | 601.2 | 199.9 | 130.8 | 65.07 | 3.49 | 227.0 | 235.1 |
| SKD-64-3 | 601.1 | 199.9 | 134.2 | 66.66 | 3.60 | 240.0 | 234.3 |
| SKD-64-4 | 601.3 | 199.9 | 133.2 | 66.37 | 3.60 | 239.0 | 239.0 |

# MMLT Couple Testing: n-legs 550-600

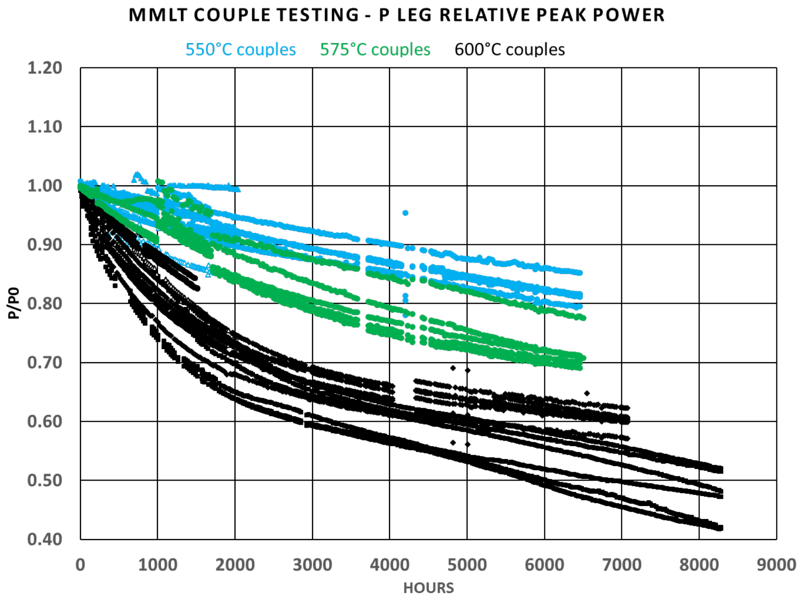


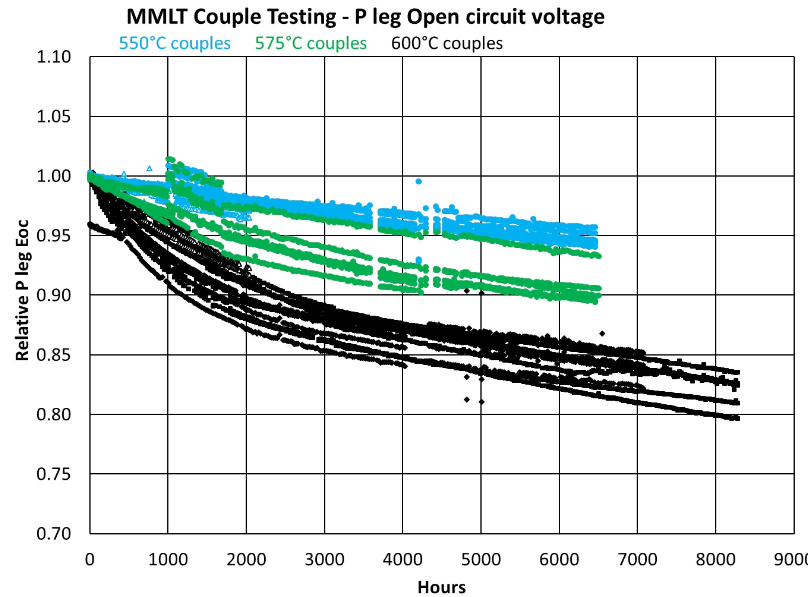



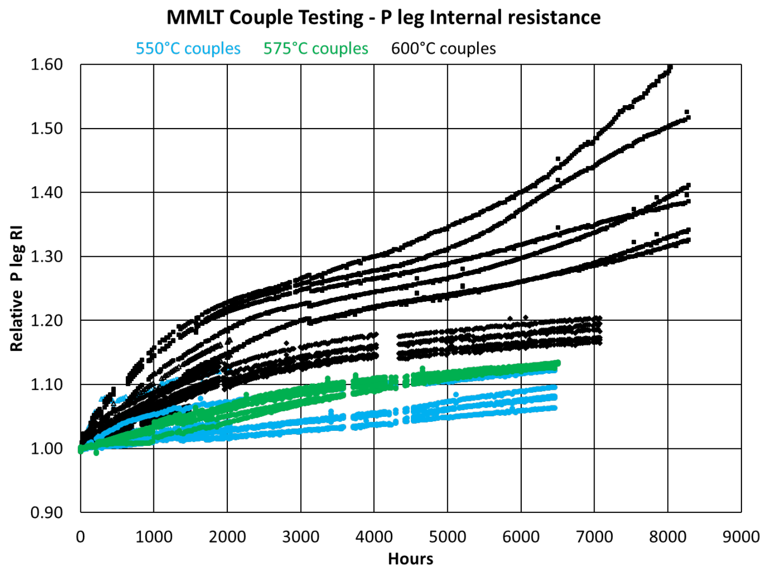




- N-legs show stable performance
- 600C actually shows slight rise in power
- Slight rise in internal resistance is compensated by rise in open circuit voltage
- Nominal Thj operating temperature is about 550C

# MMLT Couple Testing: P-legs 550-600



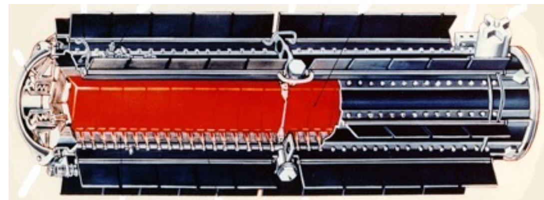



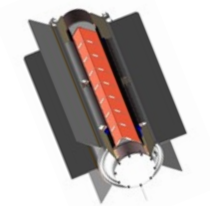

- P-legs less stable over time than n-legs
- 550 and 575° C show better performance than 600° C
- Nominal Thj operating temperature is about 550C

# What controls RTGs Lifetime Performance?

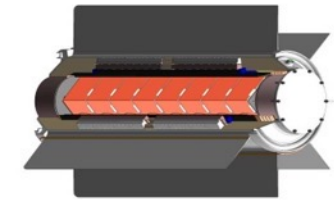
**GPHS RTG**



**eMMRTG**



**MMRTG**



**Degradation mechanisms**

1. **Fuel decay**
2. **Decrease in hot-junction as a result of decreasing heat input**
3. **Thermoelectric related mechanisms**
   - Sublimation of TE materials
   - Couple interface properties
   - Change in TE properties vs. t & T
   - Insulation thermal conductance

| GPHS RTG | eMMRTG | MMRTG |
|---|---|---|
| ~ 0.8%/year decrease in power output | | ~ 0.8%/year decrease in power output |
| + | | + |
| ~ 0.5 %/year decrease in power output | | ~ 0.5%/year decrease in power output |
| + | | + |
| Decrease in power output: ~ 0.3%/year | eMMRTG goal ~ 1.2%/year total | Decrease in power output: ~ 2.9%/year |
| = | | = |
| Decrease in power output: ~ 1.6%/year total | eMMRTG goal ~ 2.5%/year total | Decrease in power output: ~ 4.2%/year total |

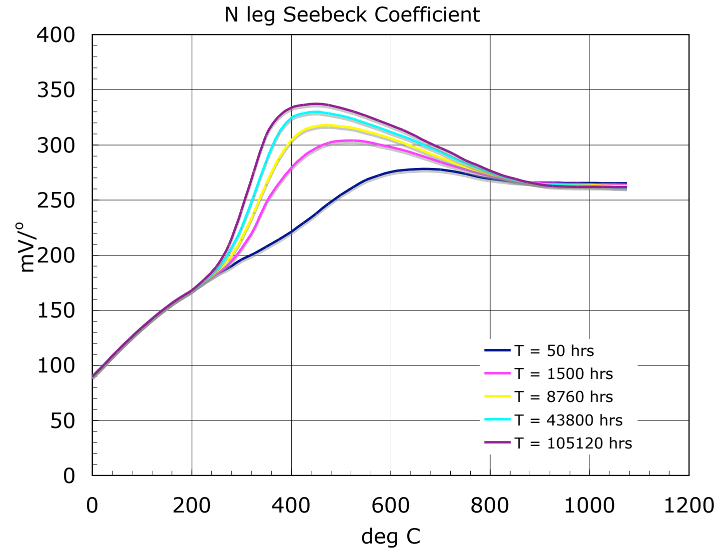
**Thermoelectric related degradation mechanisms can represent a significant fraction of the overall RTG degradation over time and need to be characterized**

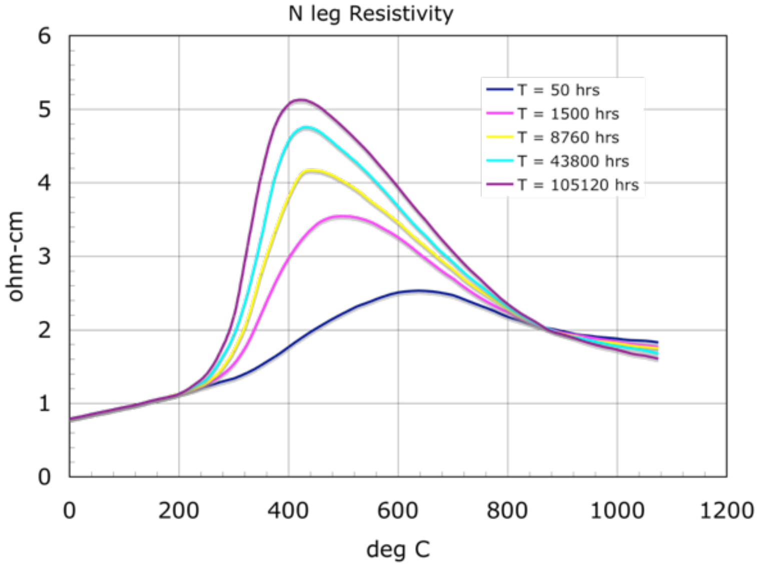
# Impact of key TE-related degradation mechanisms on RTG performance

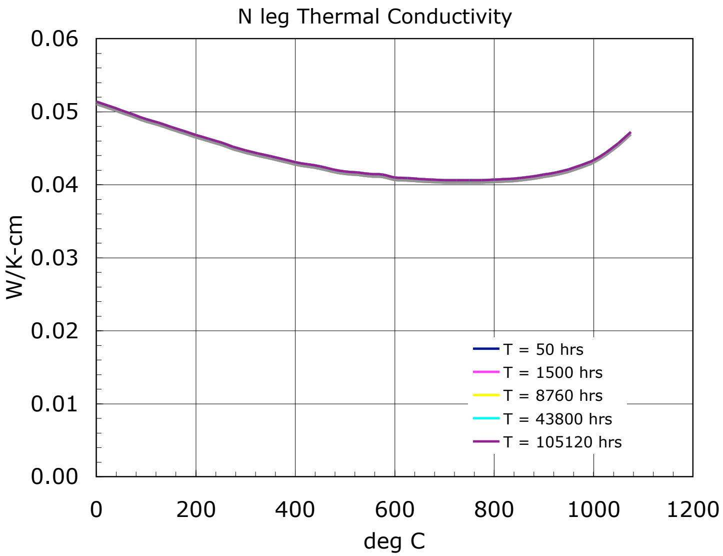
| Degradation mechanism | Key potential impact(s) | Impact(s) on generator performance |
|---|---|---|
| Sublimation of TE materials | • Increase in electrical resistance<br>• Electrical and thermal shorts<br>• Promote the degradation of couple interfaces at the hot-junctions<br>• Potentially impact all other mechanisms | • Reduced power<br>• Electrical isolation |
| Increase in electrical & thermal contact resistances at the couple interfaces | • Increase in electrical resistance<br>• Lower temperature gradient across TE elements | • Reduced power |
| Change in thermoelectric properties (Seebeck, electrical resistivity, and thermal conductivity) vs. time and temperature | • Can reduce thermoelectric efficiency if lower ZT<br>• Lower temperature gradient across TE elements if increased thermal conductivity | • Reduced power |
| Increase in thermal insulation conductance | • Increased heat losses<br>• Reduced heat flux through the thermoelectric couples | • Reduced power<br>• Thermal management |

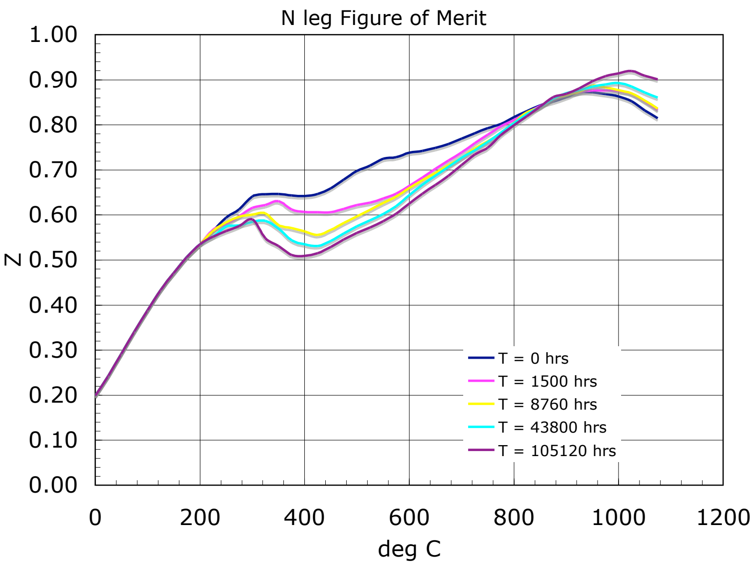
**Each TE-related degradation mechanism can have a significant impact on overall RTG degradation over time and must be quantified**

# N-SiGe Thermoelectric Property Life Data

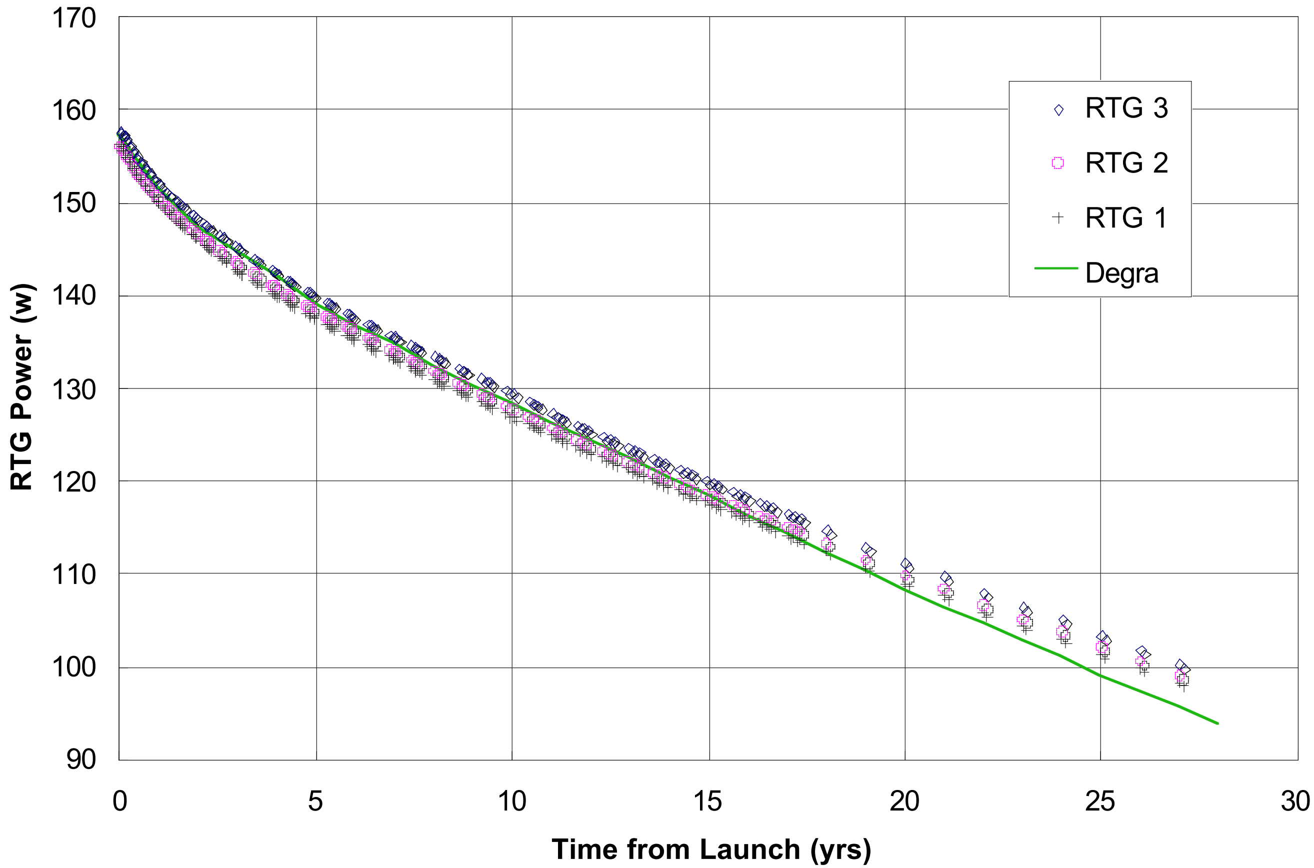


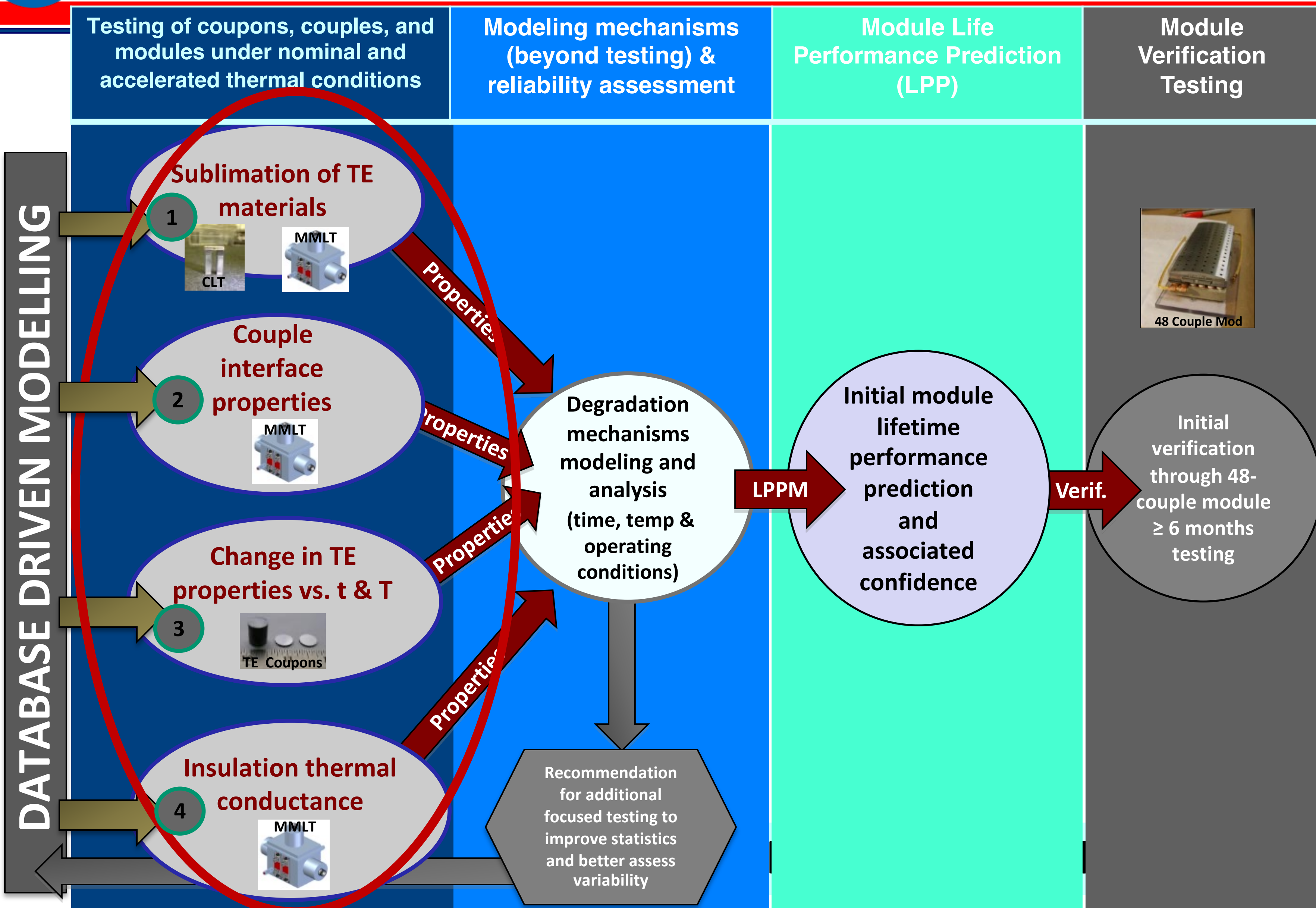



# Voyager MHW RTG Performance



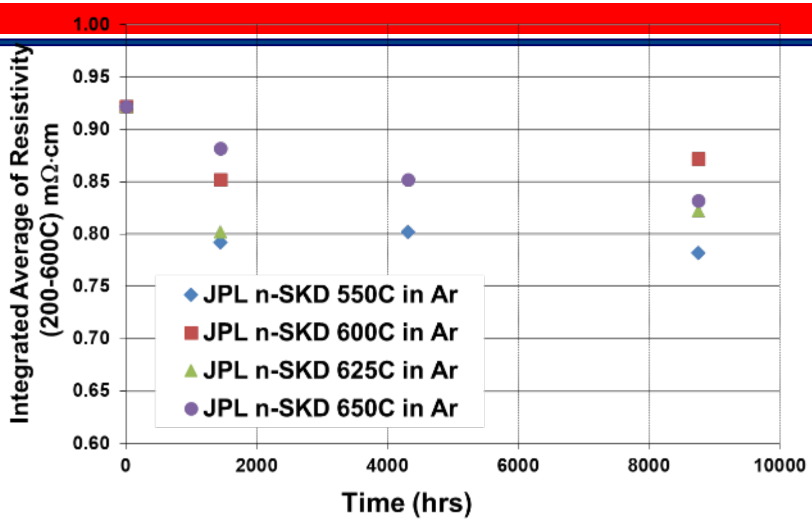

MHW-RTG’s provided power to Voyager I &II for over ≥ 30 years reliably

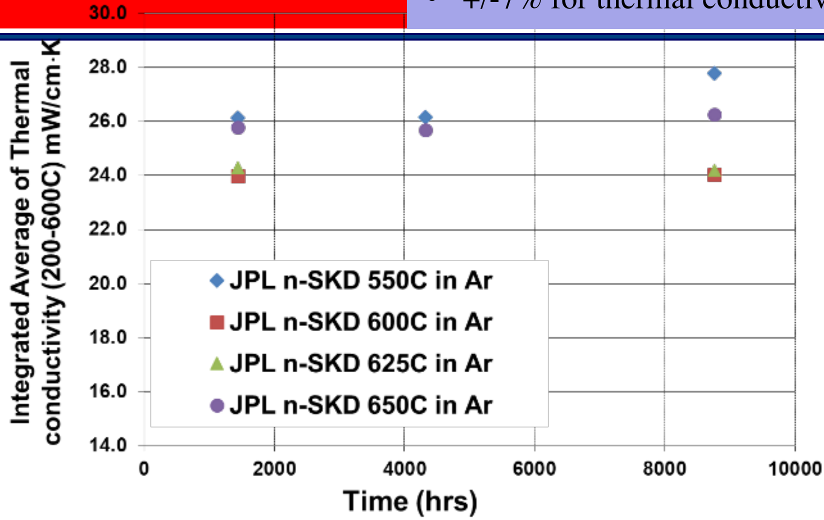
# eMMRTG Prediction Approach Lifetime Performance

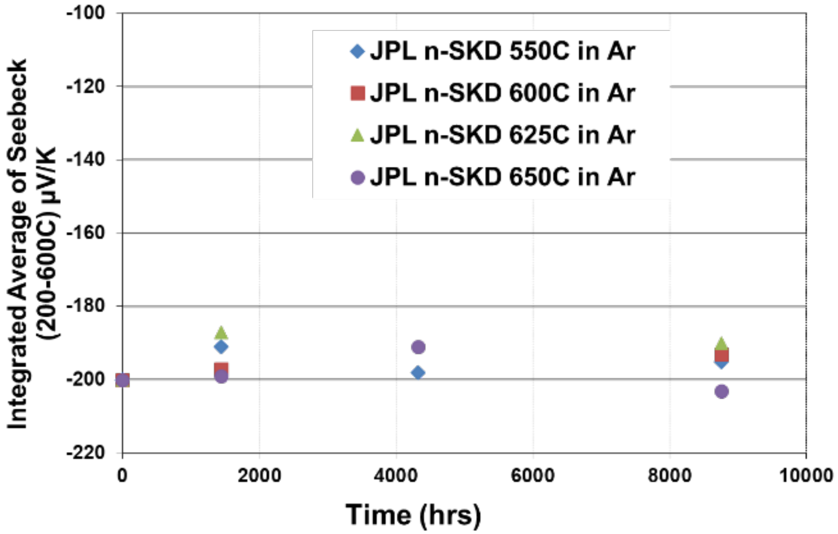


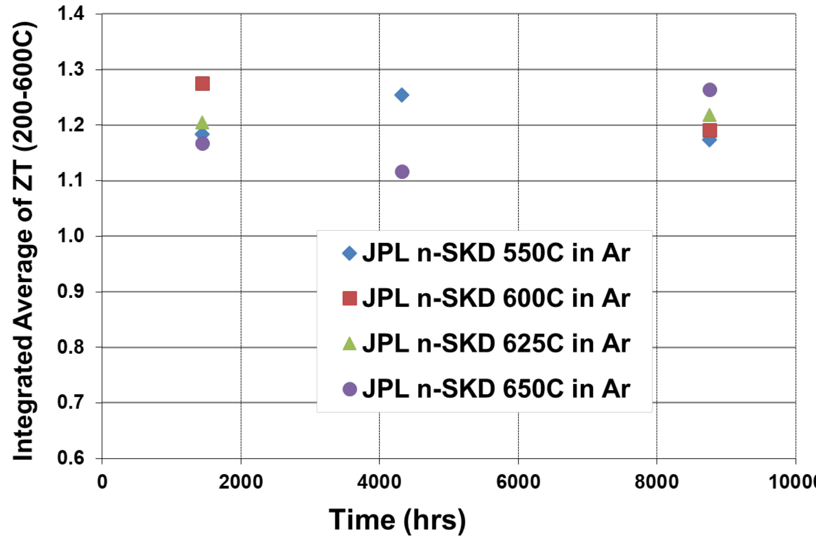
# n-SKD TE properties life testing in Ar

Measurement uncertainty:
- +/-5% for Seebeck
- +/-2% for resistivity
- +/-7% for thermal conductivity



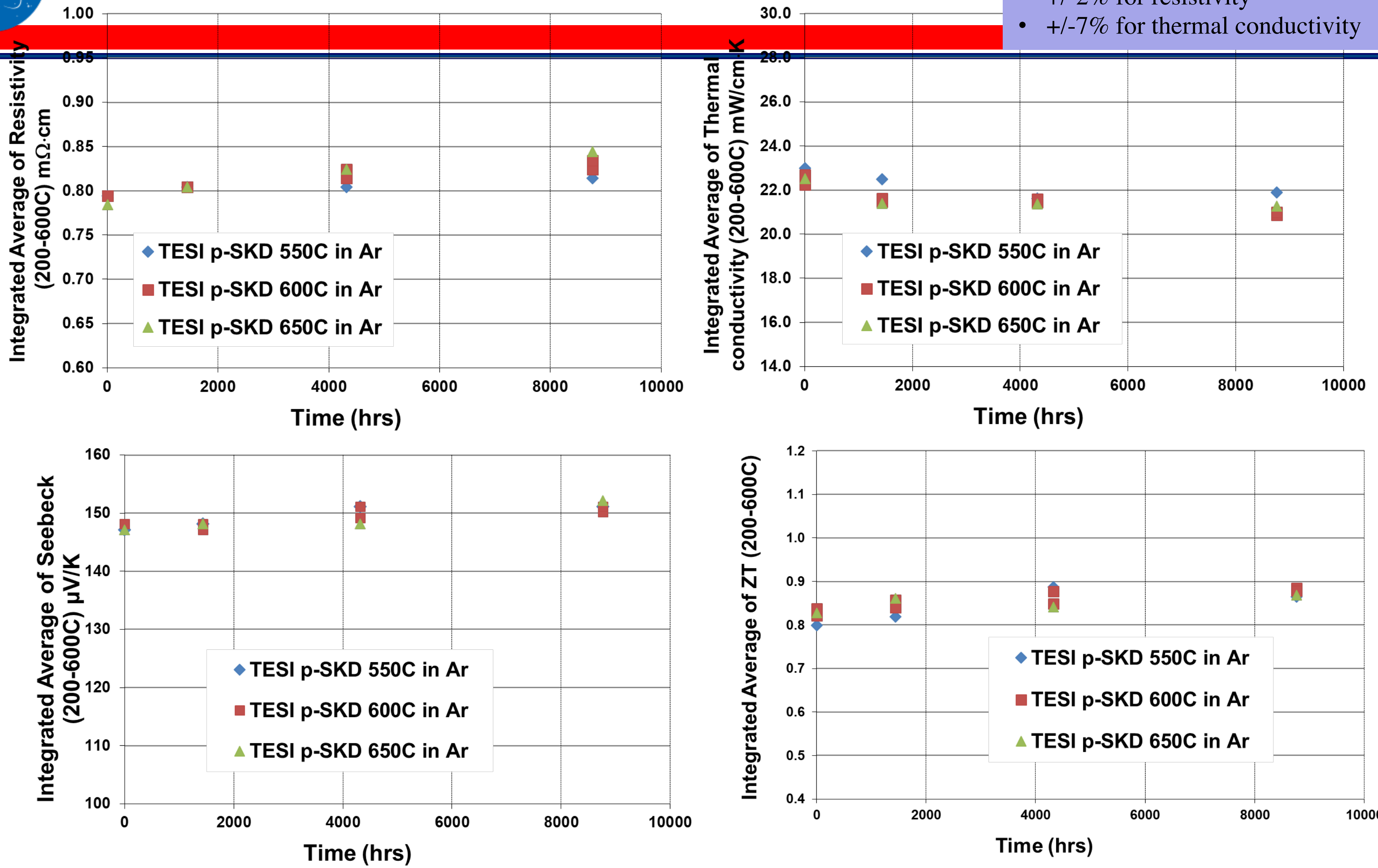




**TE properties of n-SKD show no significant trend or change over time**

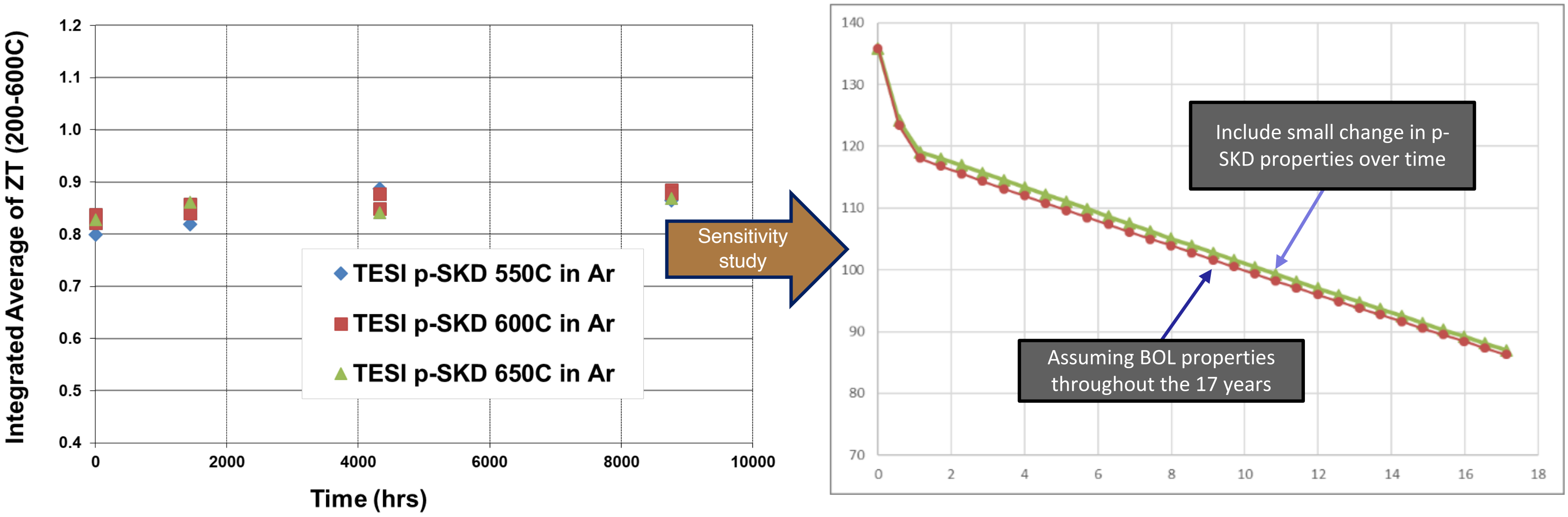
# p-SKD TE properties life testing in Ar

Measurement uncertainty:
- +/-5% for Seebeck
- +/-2% for resistivity
- +/-7% for thermal conductivity




**SKD TE properties of TESI p-SKD show a slight change, increase in ZT, over time**

# p-SKD TE properties life testing in Ar




- Including the change in p-SKD properties over time increases the EODL power by less than 0.5 W
- Small impact compare to other contributions including couple interface degradation

# TE Properties – In-Gradient Life Testing

**The couple was tested at $T_H$=600C and $T_C$=200C for 6,360 hours under continuous electrical load ~ 1.6 A**

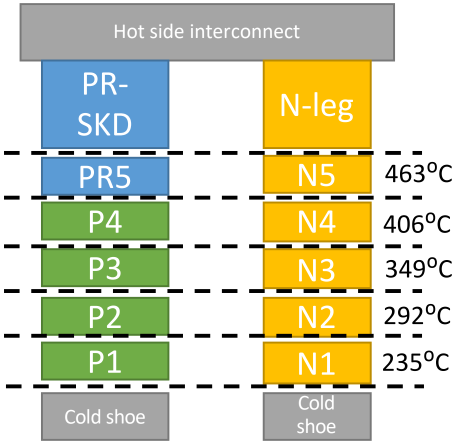
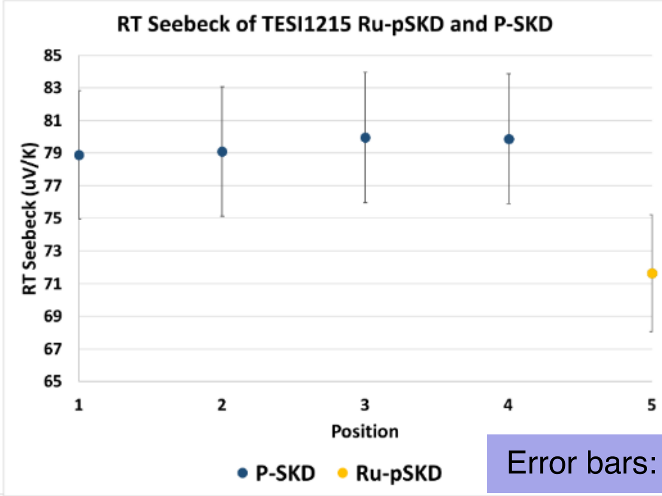
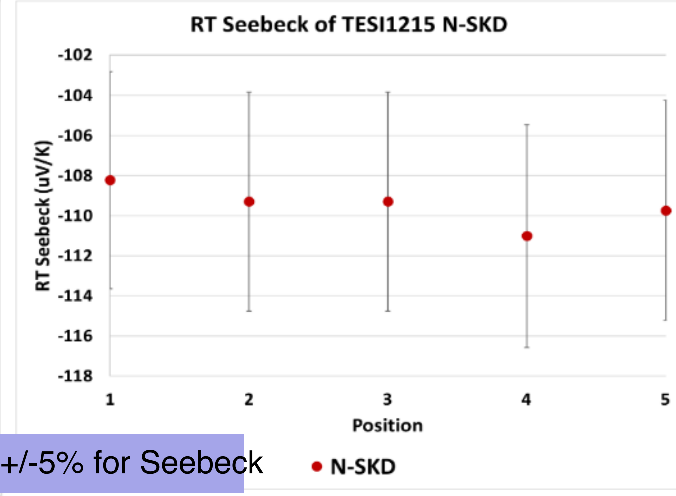
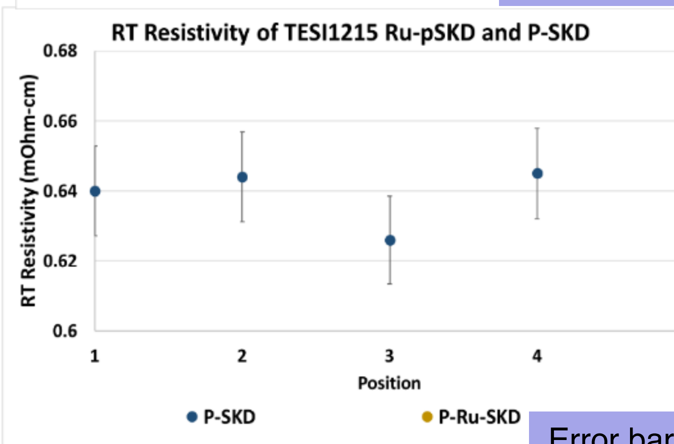


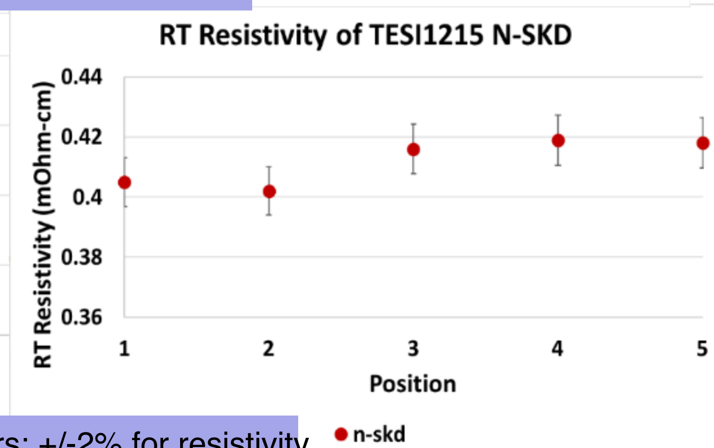

Diagram showing approximate locations and temperatures of sections diced from the SKD legs of couple 1215




Error bars: +/-5% for Seebeck




Error bars: +/-2% for resistivity

- **Slight changes observed after testing are consistent with isothermal TE property life test results**
- **No evidence of electromigration or chemically driven TE properties changes**

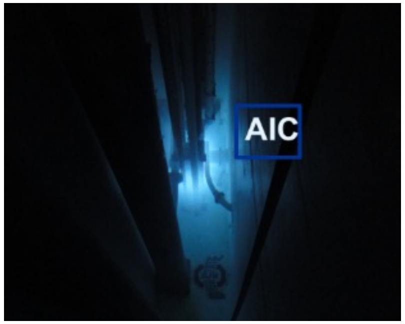
# Radiation effects on TE properties

- **Background**
  - <u>Potential impact of radiation on TE materials</u>
    - TE materials are potentially susceptible to displacement damage from radiation
    - In TE materials, lattice thermal conductivity and other properties may change due to radiation induced displacement damage
  - <u>Source of radiation</u>
    - Neutrons from spontaneous fission in undesired plutonium isotopes Pu-236, 240 and 242 in Pu-238 heat source could cause displacement damage
    - Energetic electrons and protons in Europa orbit's natural radiation environment could also cause displacement damage

☛ **Radiation testing conducted to evaluate potential impact of exposure of SKD materials to radiation**

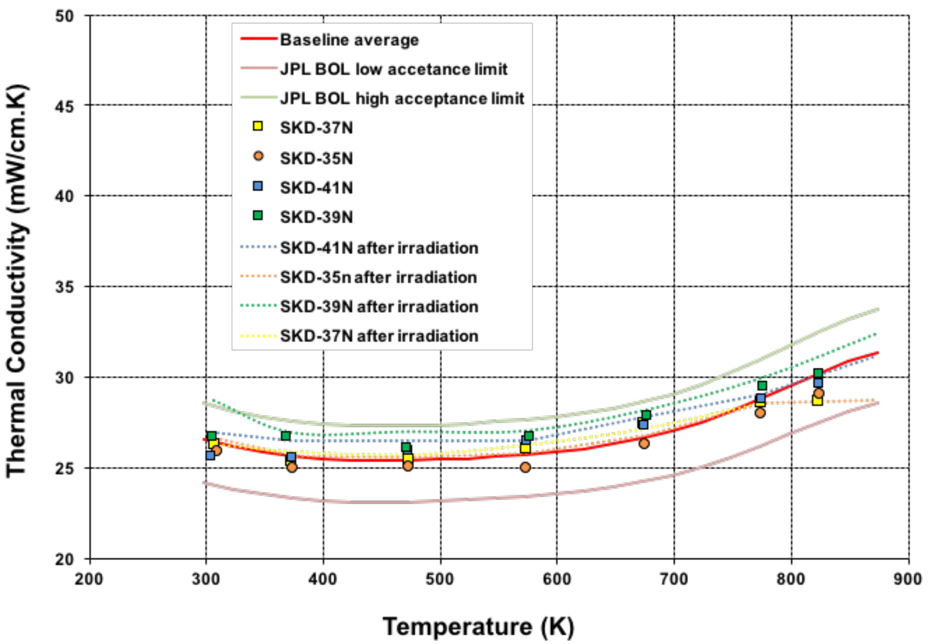
- **Test conditions**
- Need to include neutrons generated from Pu-238 heat source in the RTG and the 1MeV neutron equivalent fluence for the energetic charged particles in the Europa orbit
- When these two fluences are added together, and a radiation design factor or radiation design margin of 2 is applied, the total fast neutron fluence is estimated at $2.4 \times 10^{13}$ n/cm$^2$
- The irradiation time inside the OSU-RR at 50kW power was 48.64 minutes to achieve the targeted fast neutron fluence of $2.4 \times 10^{13}$ n/cm$^2$
- Testing was conducted near room temperature

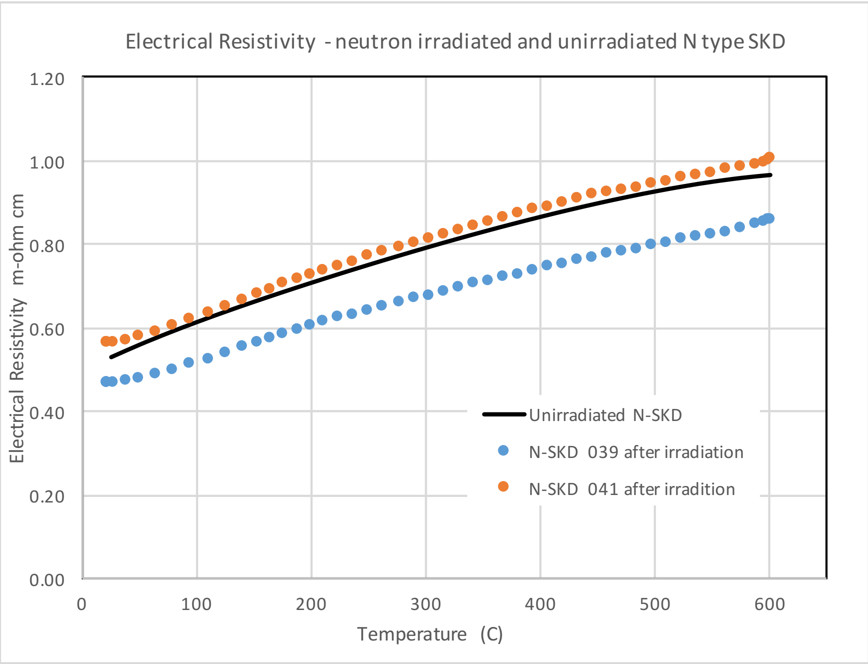
SKD coupons sealed in quartz ampoules for irradiation testing




Photograph showing the Auxiliary Irradiation Column (AIC) inside the research reactor at the Ohio State University

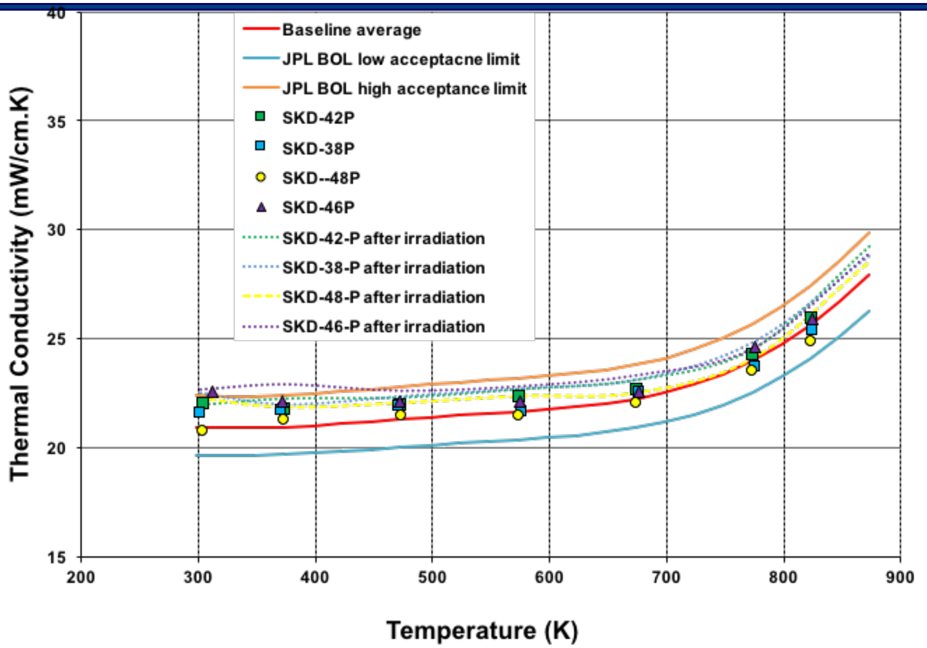
# SKD thermal conductivity after irradiation – n-type

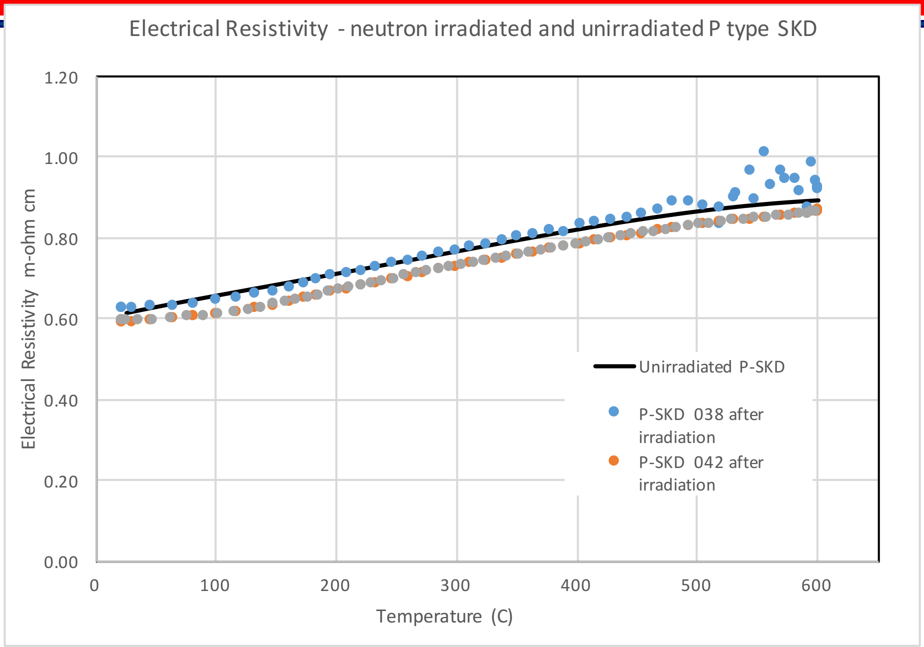



**Variations between BOL and post-irradiation are within typical measurement uncertainty**

# SKD thermal conductivity after irradiation – p-type



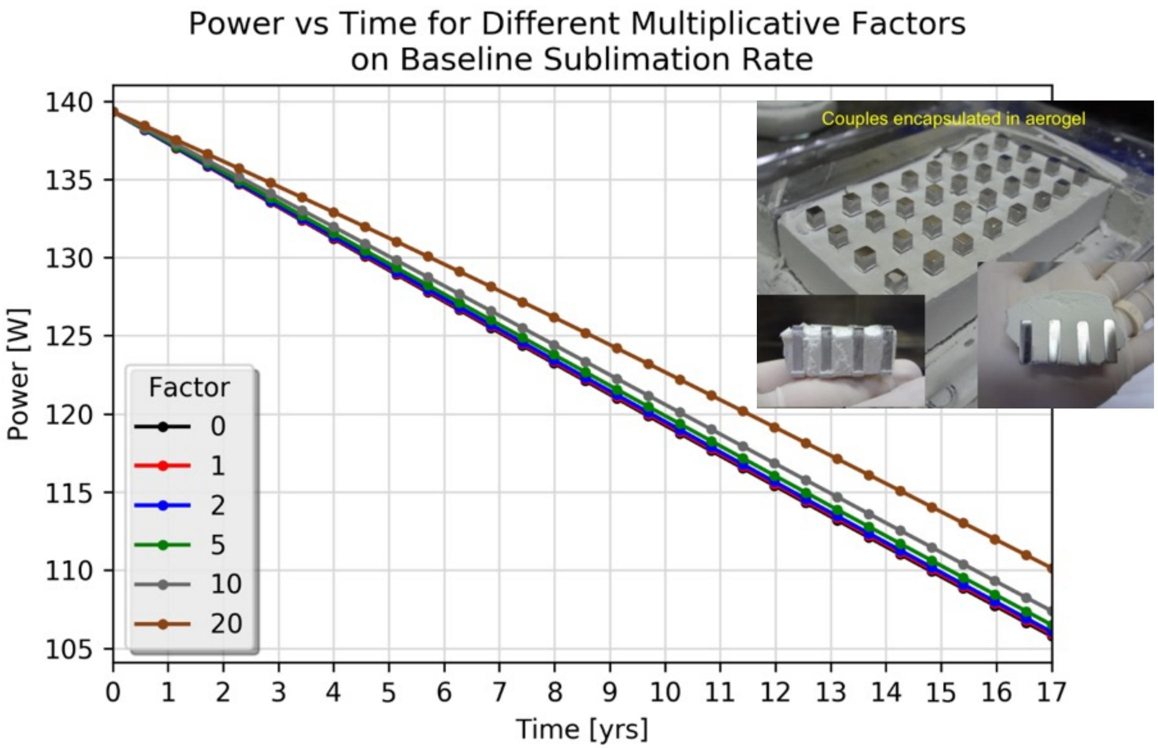

**Variations between BOL and post-irradiation are within typical measurement uncertainty**



Pre-Decisional Information – For Planning and Discussion Purposes Only

# Sublimation Rate Testing Status

| | Current best estimate of p-SKD sublimation rate in Ar with CPDA | Current best estimate of n-SKD sublimation rate in Ar with CPDA |
|---|---|---|
| At 550C | **$1.4\times10^{-8}$ g/cm$^2$/hr** | Not measurable |
| At 600C | **$1.6\times10^{-6}$ g/cm$^2$/hr** | Not measurable |
| At 650C | **$1.5\times10^{-4}$ g/cm$^2$/hr** | Not measurable |




- **Factor "0" corresponds to a no sublimation case and Factor "1" corresponds to the sublimation rate established to date for n- and p-SKD materials**
- **Sublimation rates were also artificially increased up to 20 times to conduct a sensitivity study**
- **Current estimated sublimation rates are low enough to have little effect on RTG performance**

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